CONDUCTORS AND INSULATORS

A companion to Book 2

INTRODUCTION

Different substances respond to an EMF differently.

Substances that have low resistance are considered *conductors.*

Substances with high resistances are considered *insulators.*

Substances with an “intermediate” resistances are considered semiconductors.

ATOMS AND THE PERIODIC TABLE

ATOMS

The simplest part of *ordinary matter* is the atom.

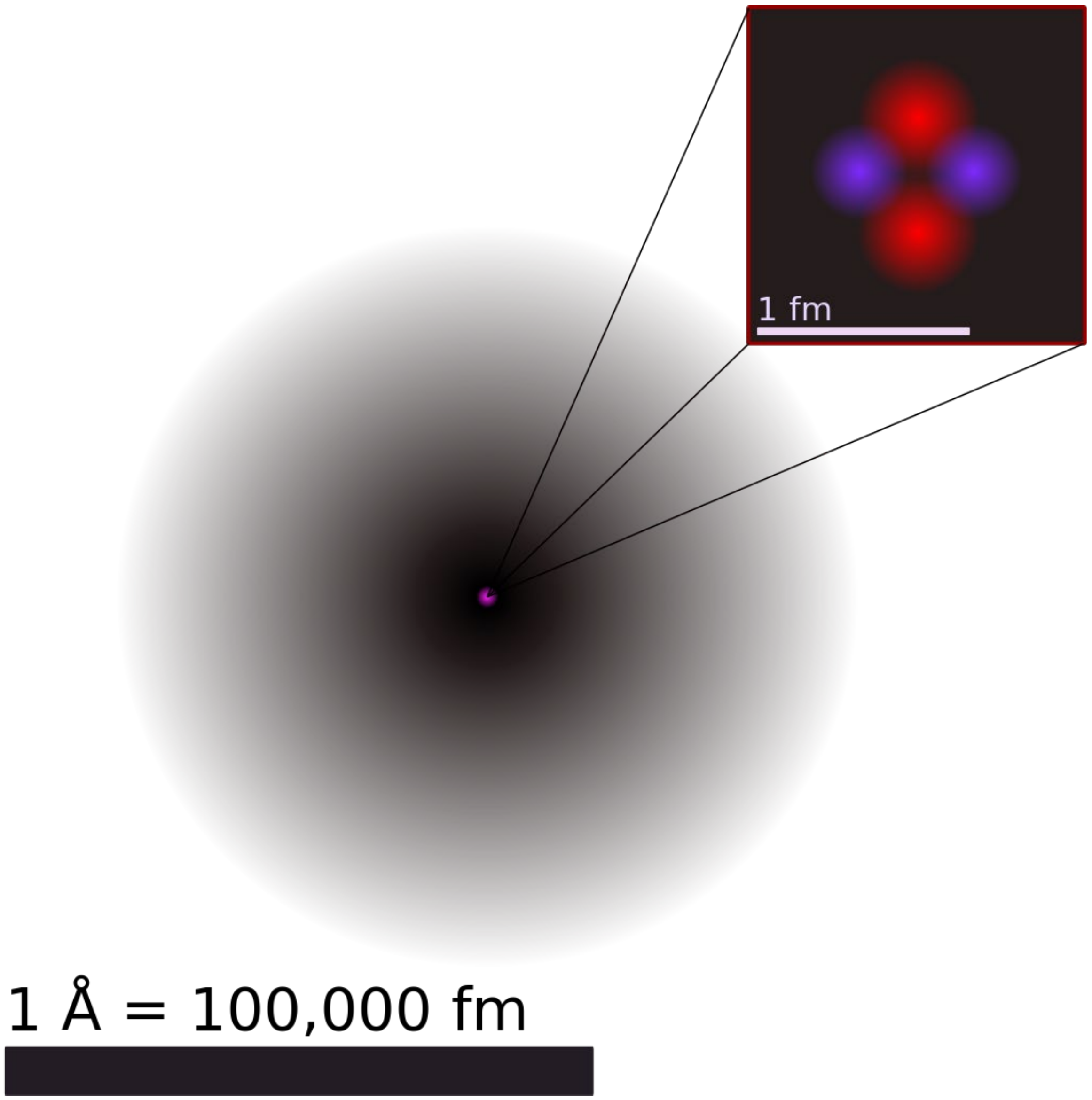
An atom consists of a positively charged *nucleus*, comprising *protons* and (except hydrogen) *neutrons*.

The atom is orbited by *electrons*.

Protons have an electric charge of +1 e.

Electrons have an electric charge of -1 e.

Neutrons have no electric charge.

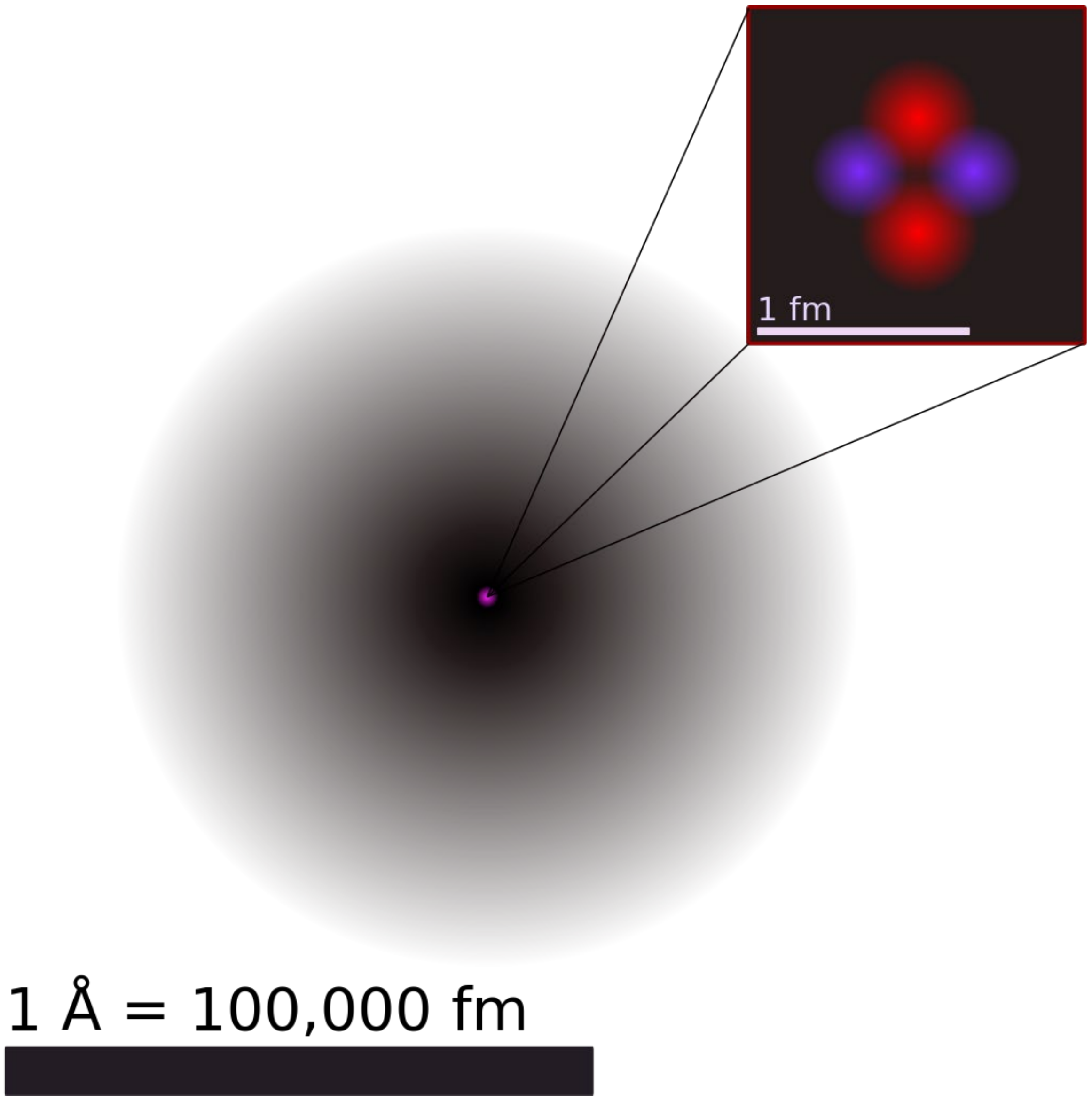


ATOMS

The picture at right shows a helium atom. A helium nucleus has two protons (red) and two neutrons (purple). The electrons orbit in the “cloud” surrounding the nucleus.

The scale is 1 Å = 10^{-10} m.

Over 99.9% of the mass of the atom is in the nucleus, but the nucleus is about 50000 times smaller than the atom itself. If the atom was the size of the Basin reserve, the nucleus would be about the size of a single grass seed.



PERIODIC TABLE

The periodic table is shown at right.

The atomic number is the number of protons in the nucleus.

Group → / Period ↓	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
				**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

PERIODIC TABLE

All elements are metals except:

Semi-metals from ^{5}B to ^{85}At: yellow-brown.

Non-metals: Yellow

Noble gases (also non-metals): Light blue

Metals and non-metals tend to form *ionic bonds* – each atom gives or takes electrons and stays permanently charged.

Non-metals and semi-metals tend to form *covalent bonds*, where the elements share electrons.

Period ↓ / Group →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac **	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

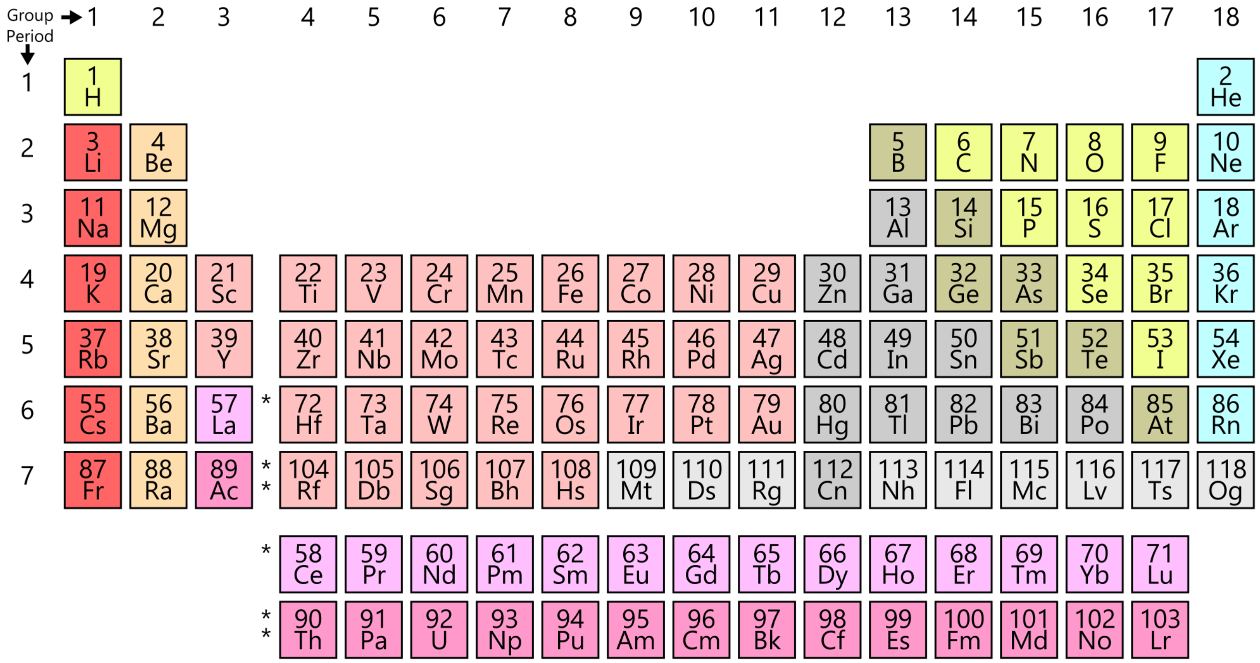
*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

PERIODIC TRENDS

The elements become less metallic from left to right.

The elements become more metallic from top to bottom.

These two competing trends cause the semi-metals to be on a diagonal line from Boron (at number 5) to Astatine (at number 85).



NOTABLE ELEMENTS

Some notable elements:

Oxygen (^{8}O), at number 8

Aluminium (^{13}Al), at 13

Silicon (^{14}Si), at 14

Copper (^{29}Cu), at 29

Silver (^{47}Ag), at 47

Tungsten (^{74}W), at 74

Gold (^{79}Au), at 79

Group → / Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
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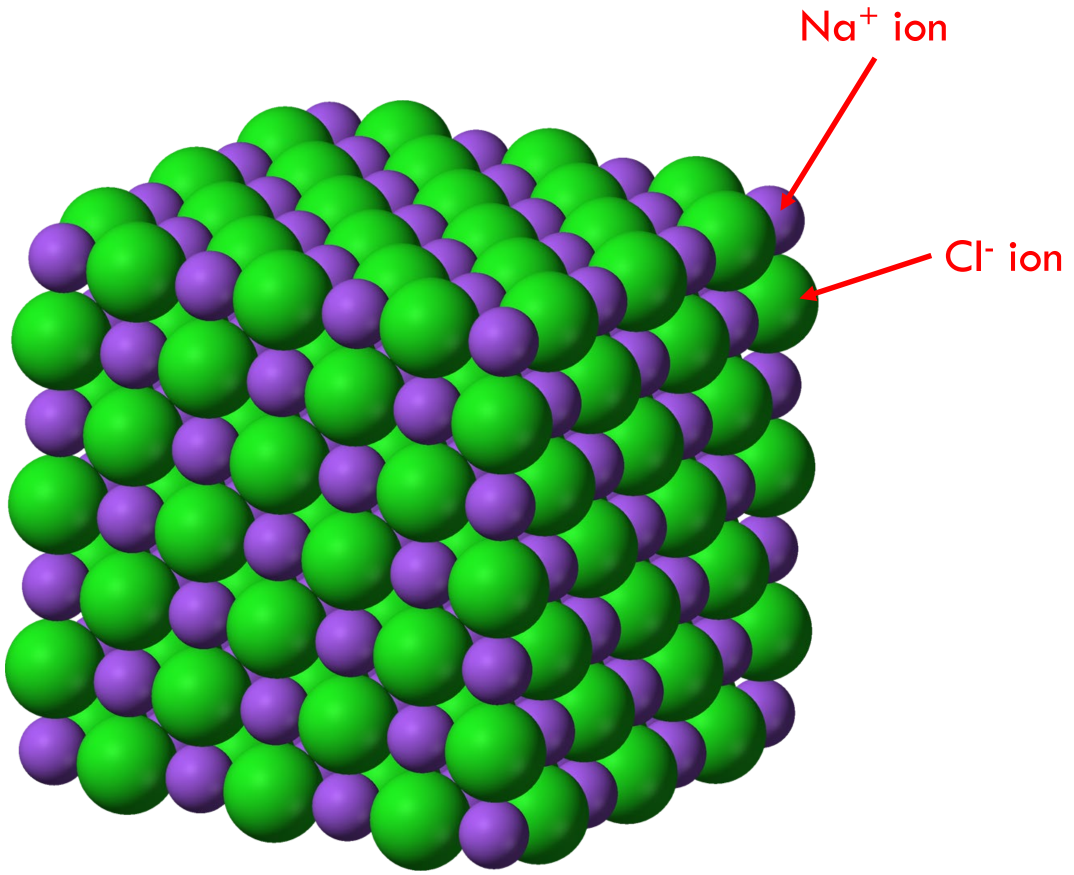
ATOMIC BONDING – IONIC

Metals, and non-metals (except noble gases) tend to form *ionic* bonds. The metal acts as an *electron donor*, and the non-metal acts as an *electron acceptor*. The atoms become permanently charged *ions*.

An example is table salt (NaCl). Table salt consists of discrete Na^+ and Cl^- ions.

Ionic substances are poor conductors unless the ions are made mobile by melting the salt, or dissolving it in water so that the ions can move.



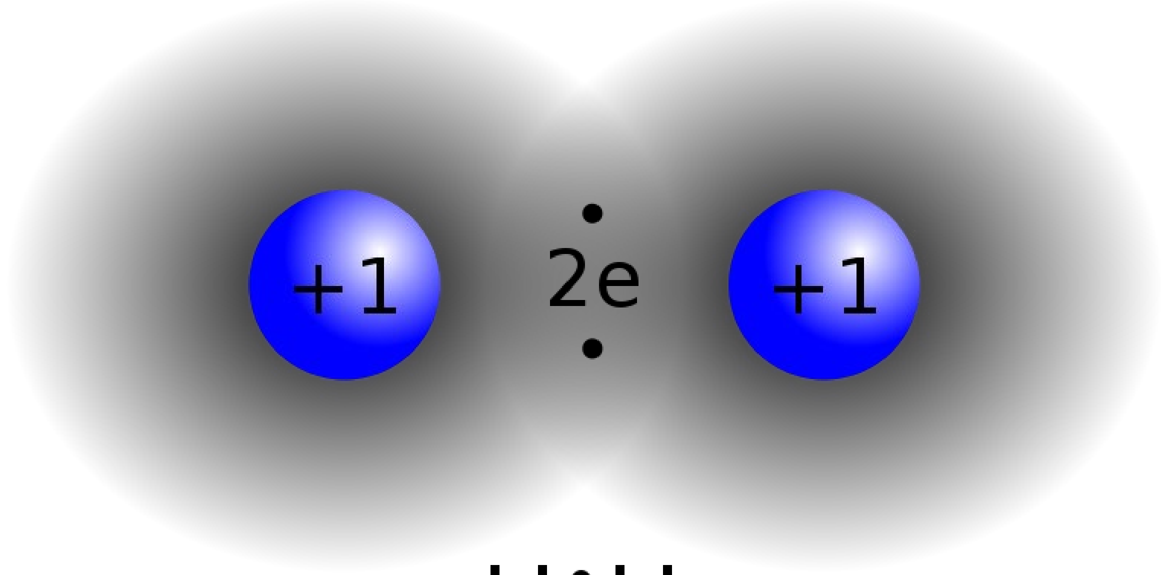
ATOMIC BONDING – COVALENT

Non-metals tend to form *covalent* bonds. Substances with covalent bonds share electrons with each other.

Examples of covalently bonded substances include plastics, nitrogen gas, sulphur.

Electrons in covalent bonds tend to be bound tightly, meaning most covalently bonded substances are poor conductors.

Hydrogen gas consists of covalently bonded H_2 molecules. The hydrogen atoms share their electrons with each other.



H:H

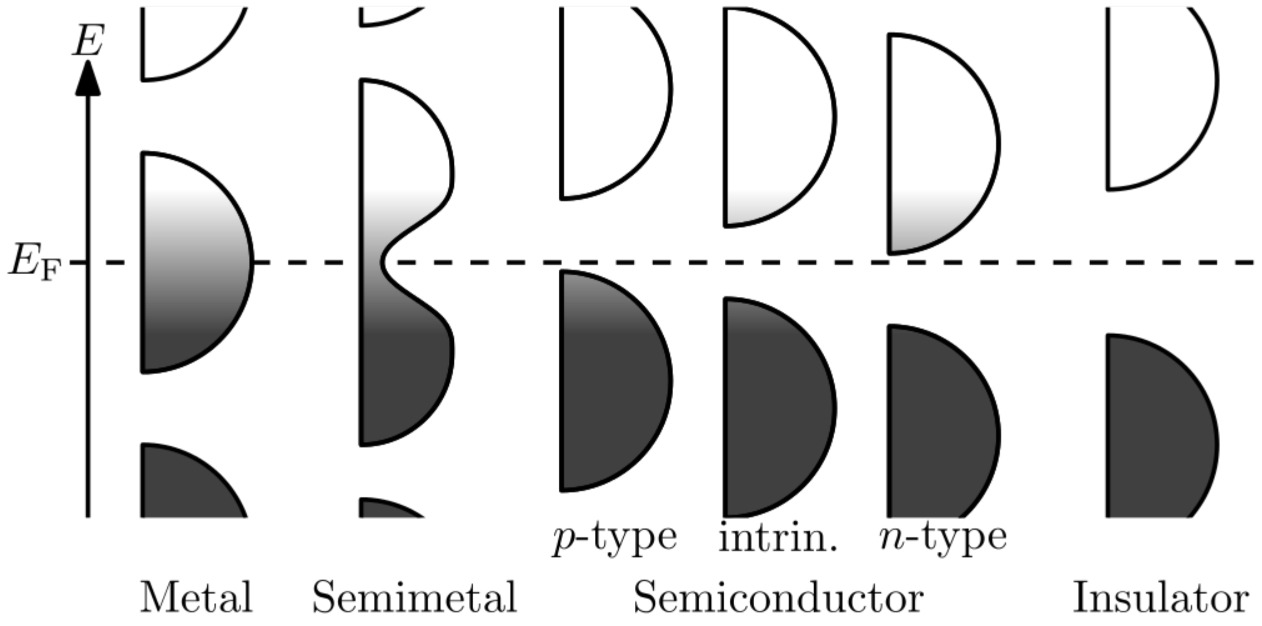
H – H

CONDUCTORS AND INSULATORS

CONDUCTORS AND INSULATORS

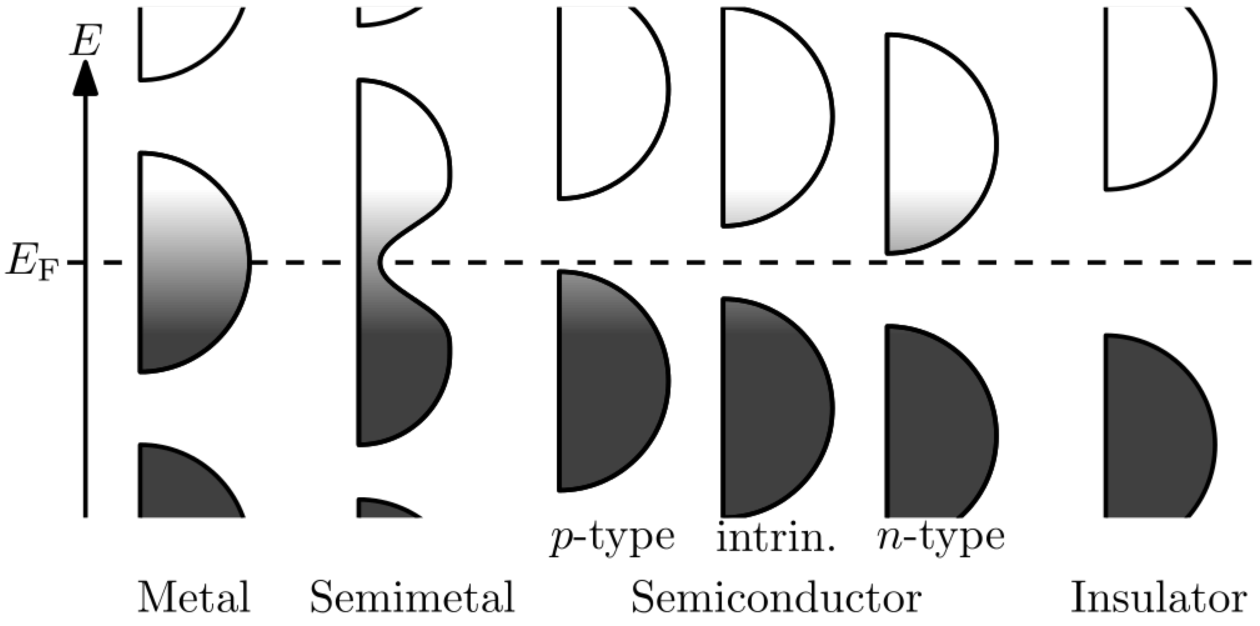
Metals have free electrons available around the *Fermi energy level* E_F . This means the electrons in metals have plenty of mobility. These properties make metals good conductors.

Insulators have no places electrons can go at the Fermi level. Therefore, the electrons in an insulator are tightly bound and not available to carry a current.



CONDUCTORS AND INSULATORS

Semimetals have some, but not many electrons available. They conduct electricity, but not well. They are also referred to as *semiconductors*. Semiconductors have conduction properties that are easily adjustable by *doping* with impurities.



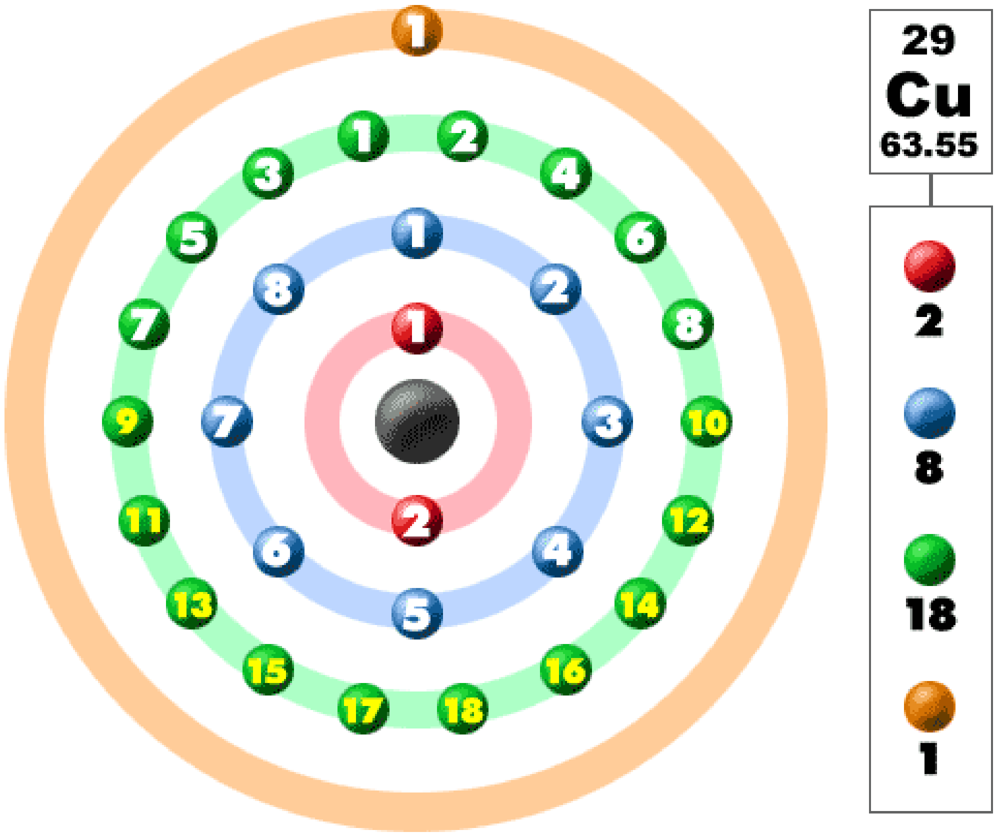
METALS –ATOMIC LEVEL

The element shown at right is copper (Cu) – atomic number 29.

Copper has a single (valence) electron in its outermost shell.

The other electron shells have: 2, 8, 18 electrons and are full.

Generally, only the valence electrons are available for electrical conduction.

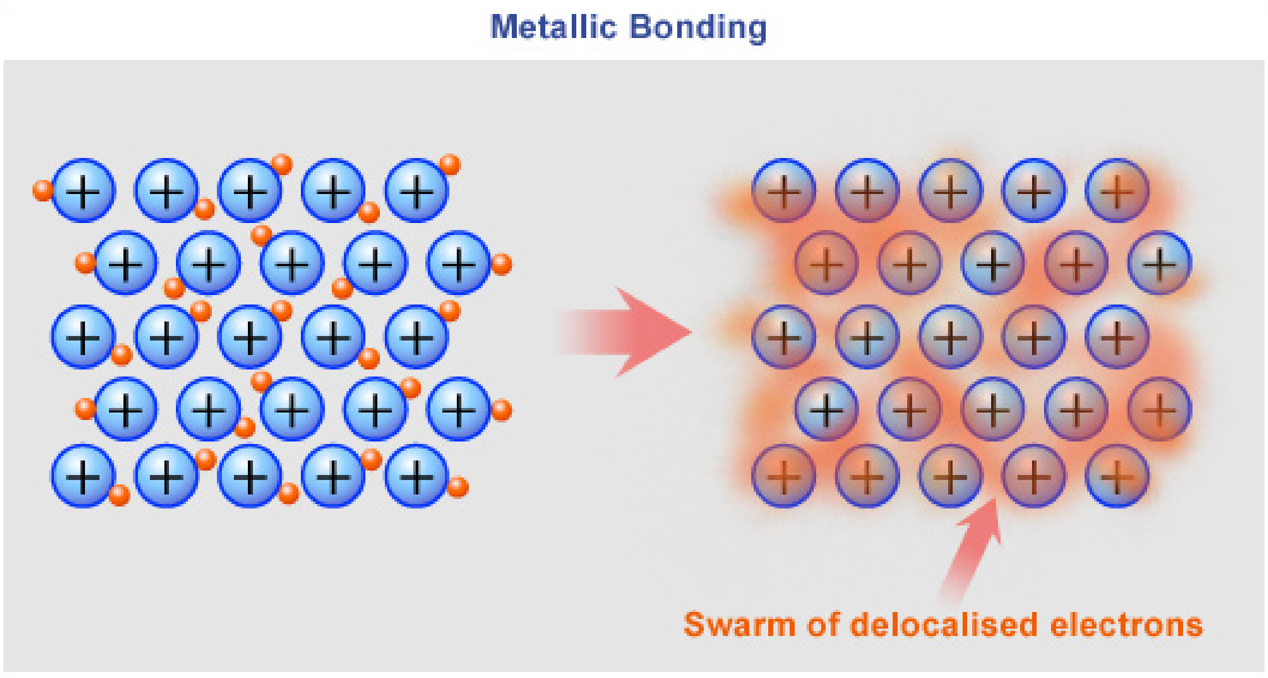


METALS - AS CONDUCTORS

Metals do not hold their outer valence electrons very strongly.

The electrons are free to "wander" through the metallic crystal under the influence of electric and magnetic fields.

This effect produces an "electron gas" – responsible for metallic properties like shiny surfaces, and good electrical and thermal conductivity.



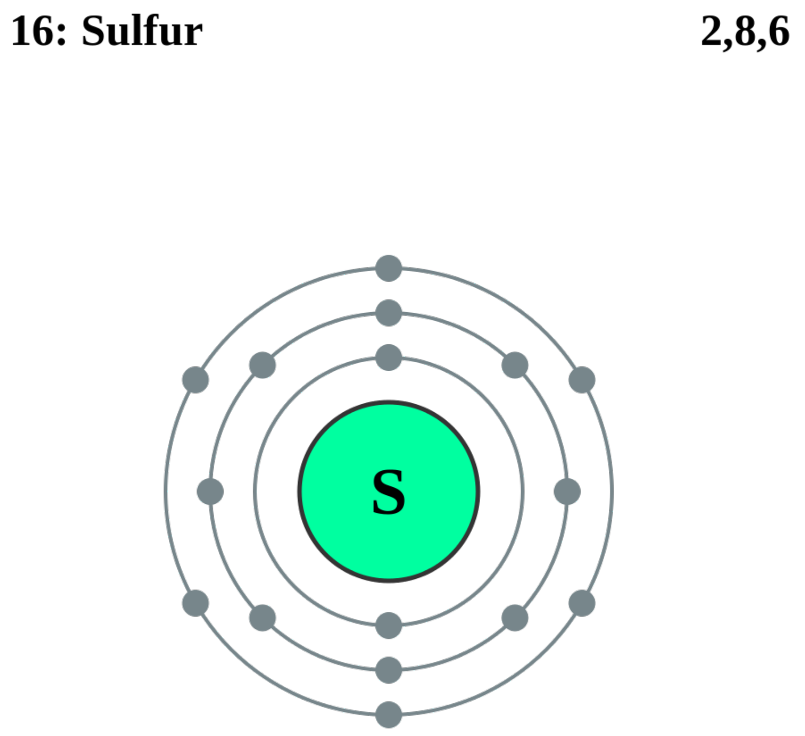
The outer electrons are so weakly bound to metal atoms that they are free to roam across the entire metal. Having 'lost' their outer electrons, individual metal atoms are more like positive ions in a swarm of communal electrons.

NON-METALS – ATOMIC LEVEL

The atom at the right is sulphur. Sulphur's outer electron shell is two electrons short.

Sulphur generally tries to "steal" or "share" two electrons to complete the shell.

Sulphur can do this with other atoms, or share electrons with other sulphur atoms.



NON-METALS – AS INSULATORS

Sulphur usually exists at 8-ringed S_8 molecules.

Sulphur is an insulator, as the sulphur atoms tightly hold their electrons.

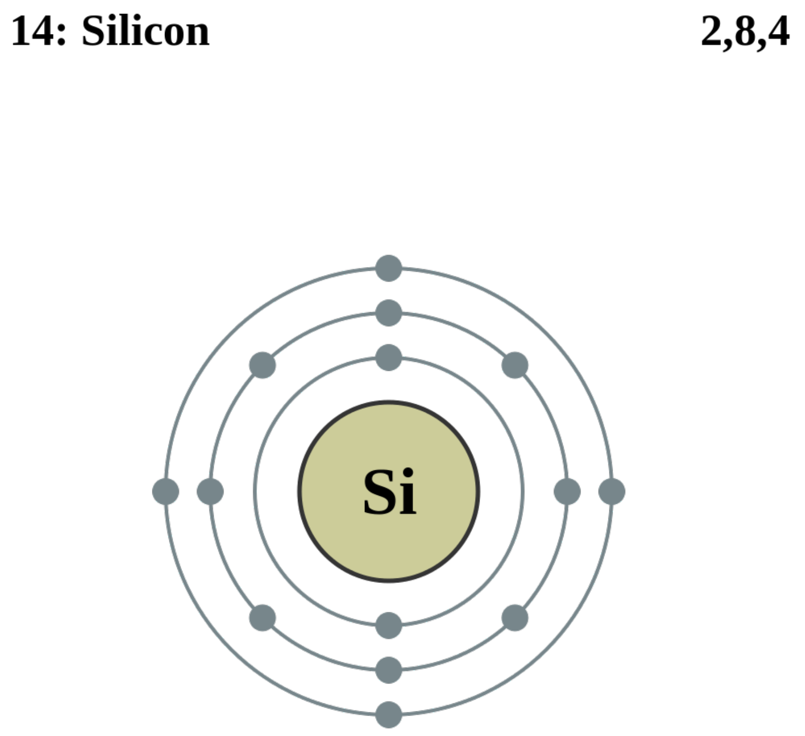
Note that sulphur is bright yellow, and lacks a metallic lustre.

SEMIMETALS – ATOMIC LEVEL

Semimetals (or metalloids) have properties intermediate between metals and non-metals.

The atom at the right is silicon. Silicon has a half full outer electron shell.

Silicon is equally able to share electrons with other silicon atoms as hold onto them.

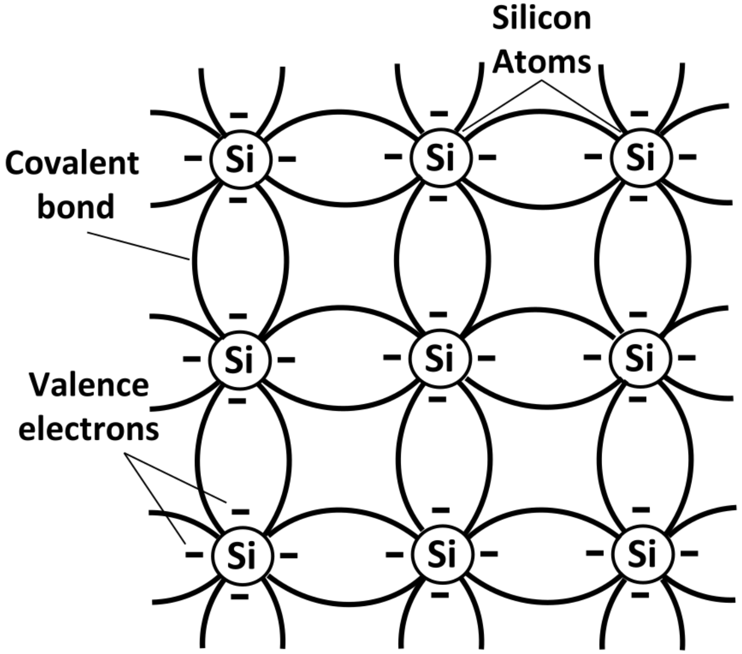


SEMIMETALS – AS SEMICONDUCTORS

Their electrons are held more strongly than metals, but are still *reasonably* free to move.

The electron freedom tends to increase with temperature.

Semimetals may be shiny, but also tend to have non-metallic properties like brittleness and significantly higher resistivity.



IONS – AS CONDUCTORS

Solid salt is not a conductor: the ions cannot move. Ionic salts can conduct if the ions are made mobile, by either melting the salt, or dissolving the salt in water.

Since the ions are electrically charged, applying a voltage to an ion solution will cause the ions to move.

The Na^{+} ions will move with the current, the Cl^{-} ions will move against the current.

RESISTIVITY

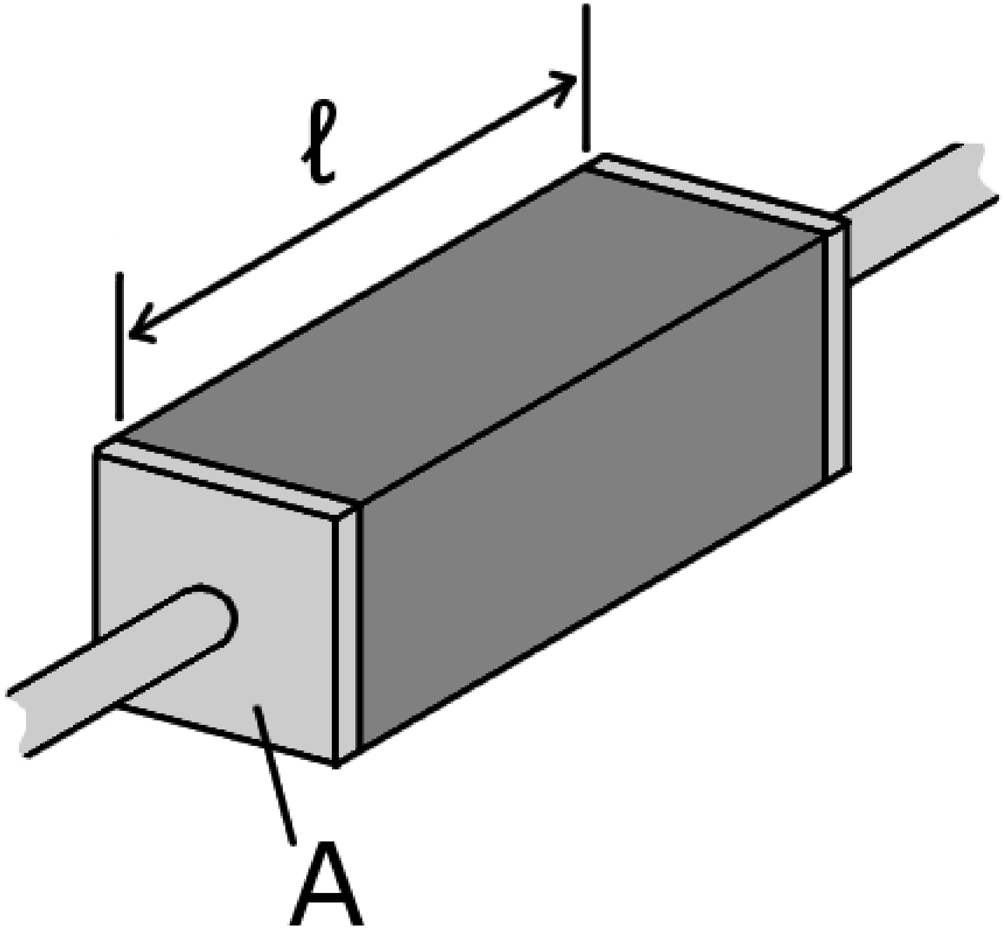
RESISTIVITY

The resistivity of a substance reflects how difficult it is to make current flow through the substance. It is *scale-invariant* the resistivity does not depend on the size of the sample.

Resistivity has the symbol ρ, and units of **Ωm** (ohm-metres). It is described by:

$$\rho = \frac{E}{J}$$

Where E is the electric field strength ($V\ m^{-1}$) and J is the current density ($A\ m^{-2}$). The resistivity is used in the resistance formula:

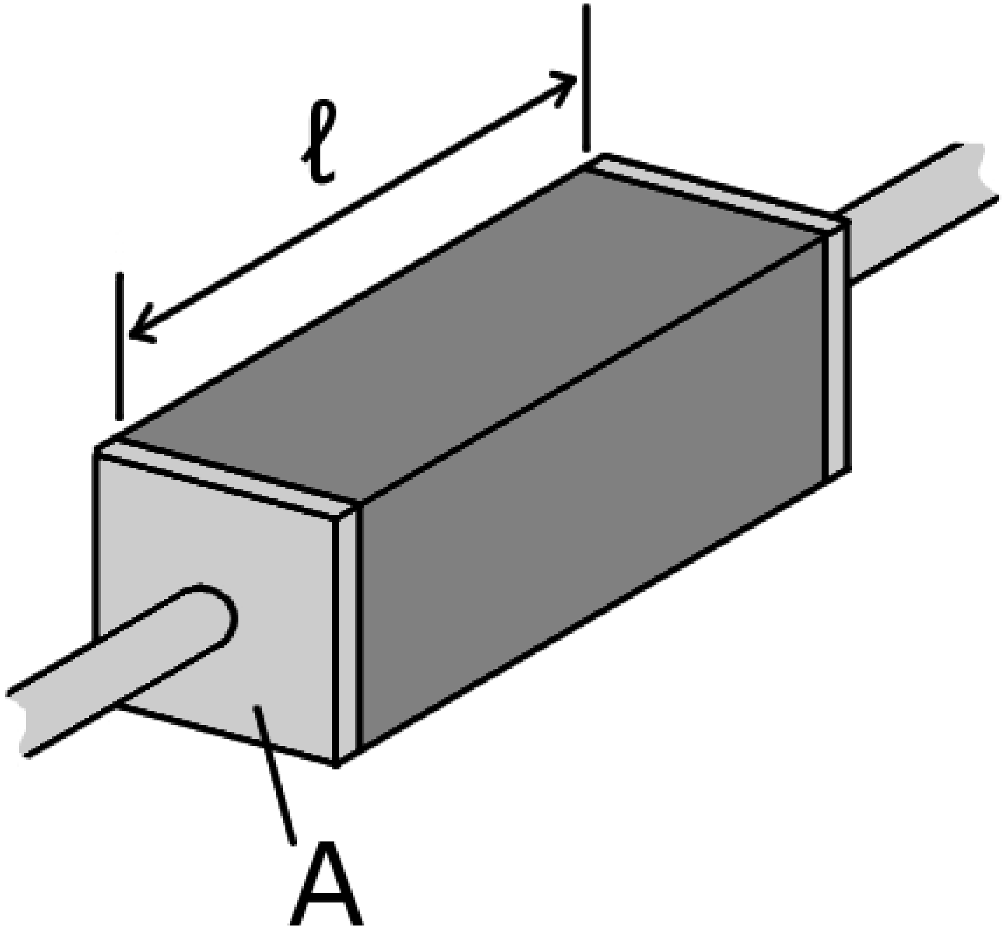


RESISTIVITY

The resistivity is used in the resistance formula:

$$R = \frac{\rho l}{A}$$

Where R is the resistance (Ω), l is the length of the conductor (m), and A is the conductor area (m^2).



CONDUCTIVITY

The conductivity is the reciprocal of the resistivity. Sometimes it's easier to say a material has high conductivity than low resistivity.

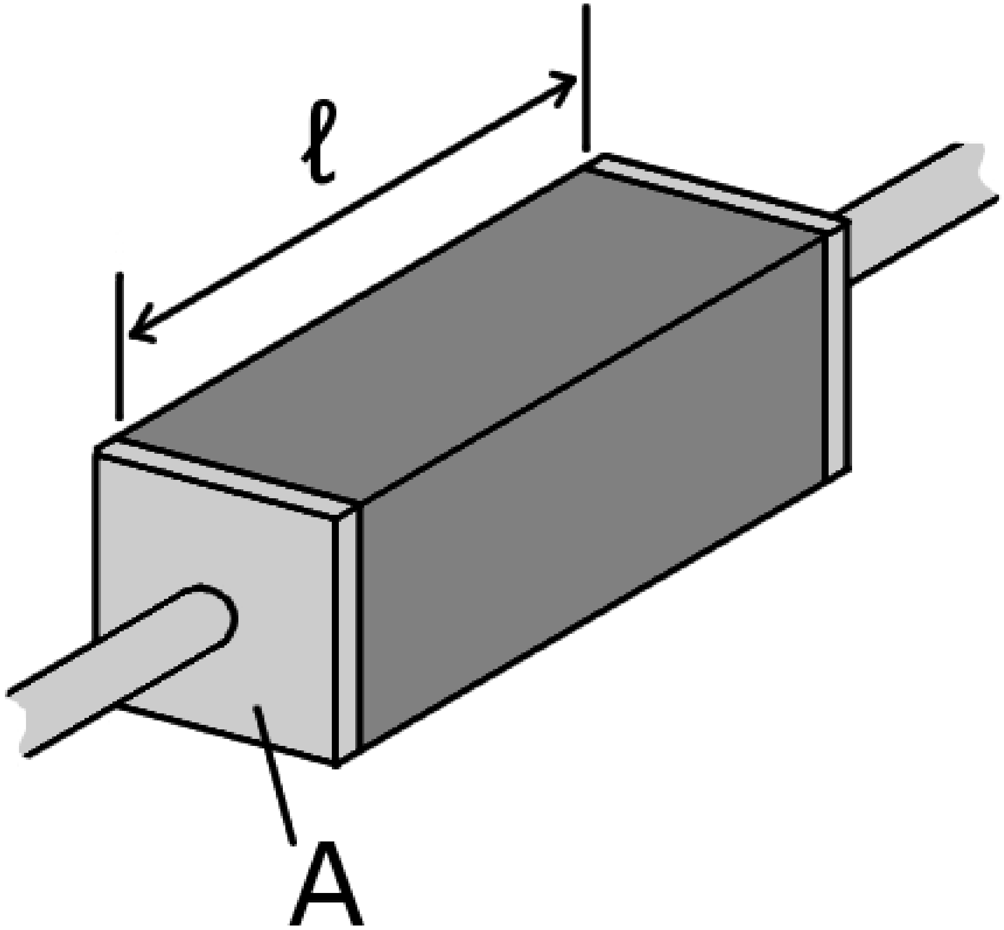
Conductivity has the symbol σ, and units of **S m^{-1}** (Siemens per metre). It is described by:

$$\sigma = \frac{1}{\rho}$$

The conductivity is used in the resistance formula:

$$R = \frac{l}{\sigma A}$$

Where R is the resistance (Ω), l is the length of the conductor (m), and A is the conductor area (m^2).



RESISTIVITY - EXAMPLES

Silver: 1.59×10^{-8} Ωm (best conductor)

Copper: 1.68×10^{-8} Ωm

Gold: 2.44×10^{-8} Ωm

Aluminium: 2.65×10^{-8} Ωm

Tungsten: 5.6×10^{-8} Ωm

Iron: 9.70×10^{-8} Ωm

Nichrome: 1.10×10^{-6} Ωm

Carbon: 5×10^{-4} Ωm

Germanium: 0.46 Ωm

Silicon: 640 Ωm

Glass: 10^{11} to 10^{15} Ωm

PVC: 10^{12} to 10^{15} Ωm

Hard rubber: 10^{13} Ωm

Air: 10^{9} to 10^{15} Ωm

Sulphur: 10^{15} Ωm (best solid element)

Fused quartz: 7.5×10^{17} Ωm

PET: 10^{21} Ωm

Teflon: 10^{23} to 10^{25} Ωm

SEMICONDUCTORS

Semimetals (e.g. silicon or germanium) have electrical properties that are easily changed by being *doped* with small amounts of *donor material* or *acceptor material*. Silicon has 4 valence electrons.

Silicon is referred to as a *base material* or an *intrinsic semiconductor*.

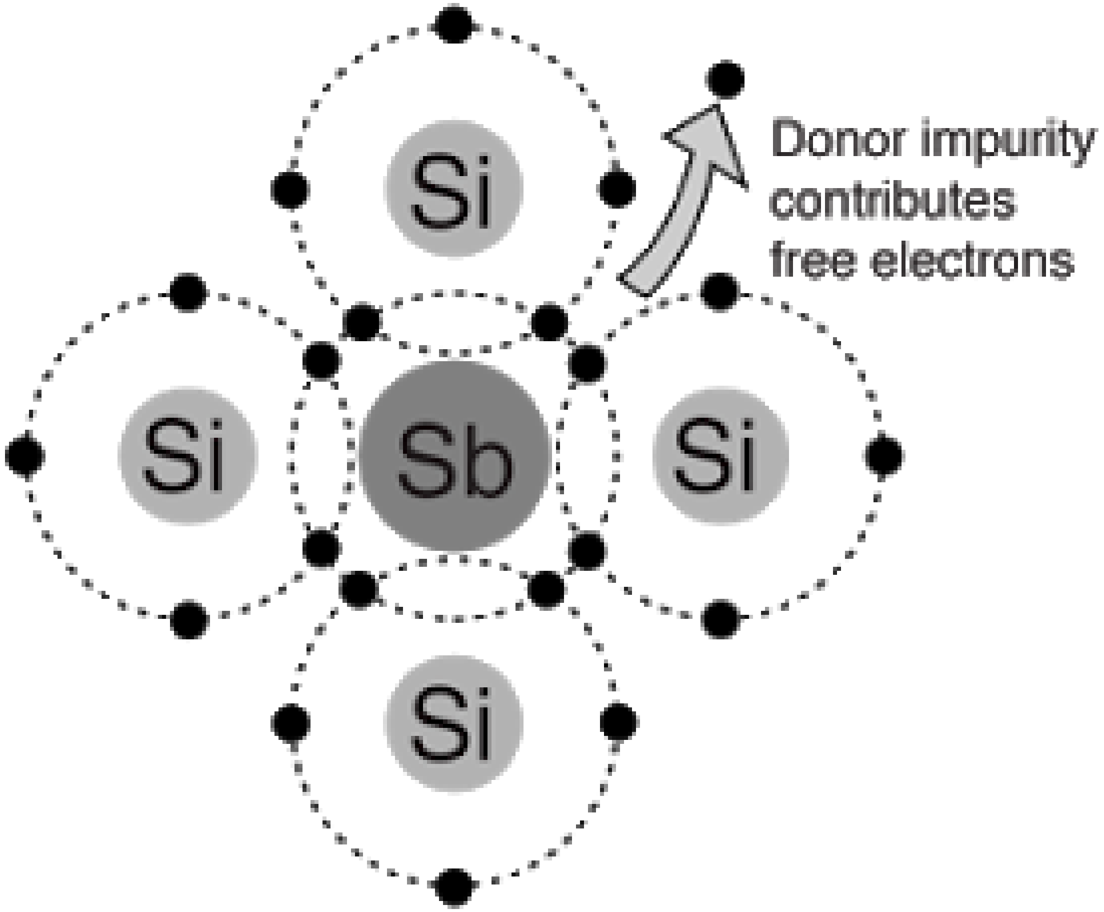
Silicon is 'doped' with impurities to alter its electrical properties. The level of doping is a few parts per million.

DONOR MATERIALS – N TYPE

Donor materials have 5 valence electrons (i.e. are *pentavalent*) e.g. phosphorus (P), arsenic (As), antimony (Sb).

Donor materials create extra free electrons in the silicon crystal lattice. Such a material is called an *n-type semiconductor*.

The picture on the right shows silicon being doped with antimony. The antimony atom gives an extra free electron.

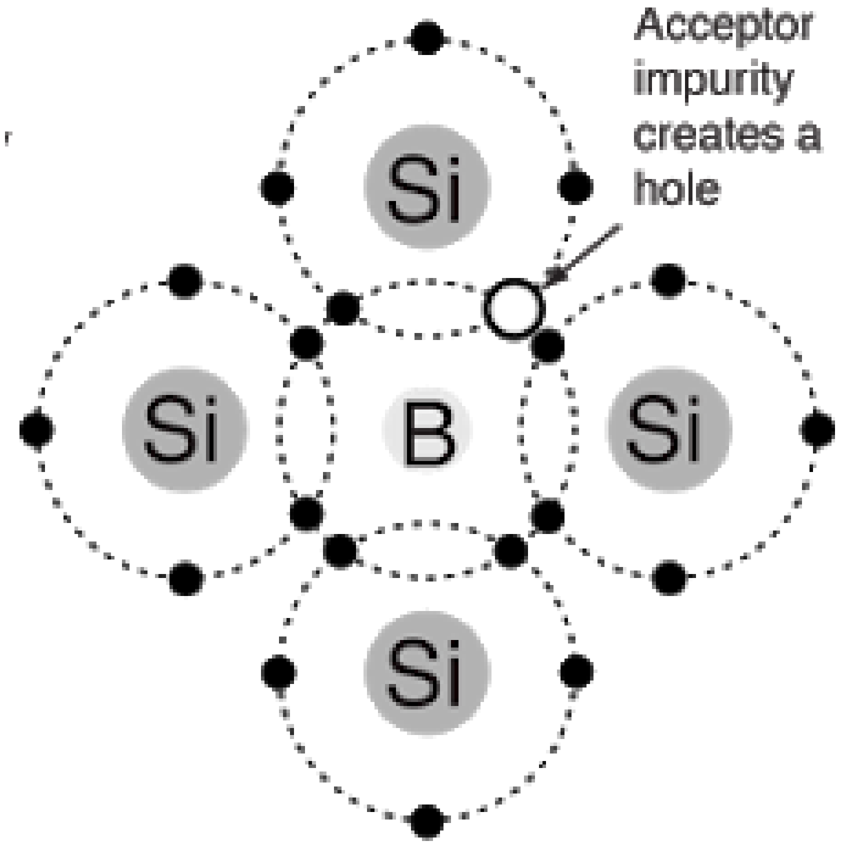


ACCEPTOR MATERIALS – P TYPE

Acceptor materials have 3 valence electrons (i.e. are *trivalent*) e.g. boron (B), aluminium (Al), gallium (Ga).

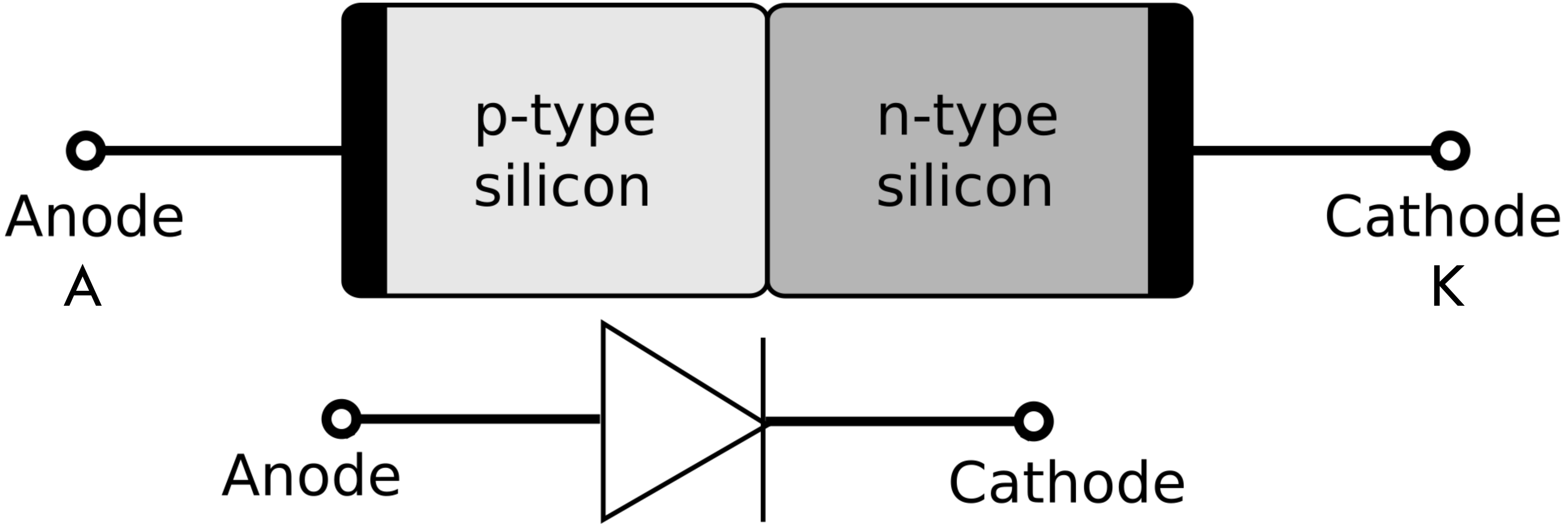
Acceptor materials create electron vacancies (holes) in the silicon crystal lattice. Such a material is called a *p-type semiconductor*.

The picture on the right shows silicon being doped with boron. The boron creates a hole, since boron has three outer electrons rather than four.



THE DIODE

Pairing up p-type and n-type semiconductors creates a diode.
A diode will permit current flow in one direction only.
The diode below permits current flow from anode (A) to cathode (K) only.



EXAMPLES OF CONDUCTORS

GOLD

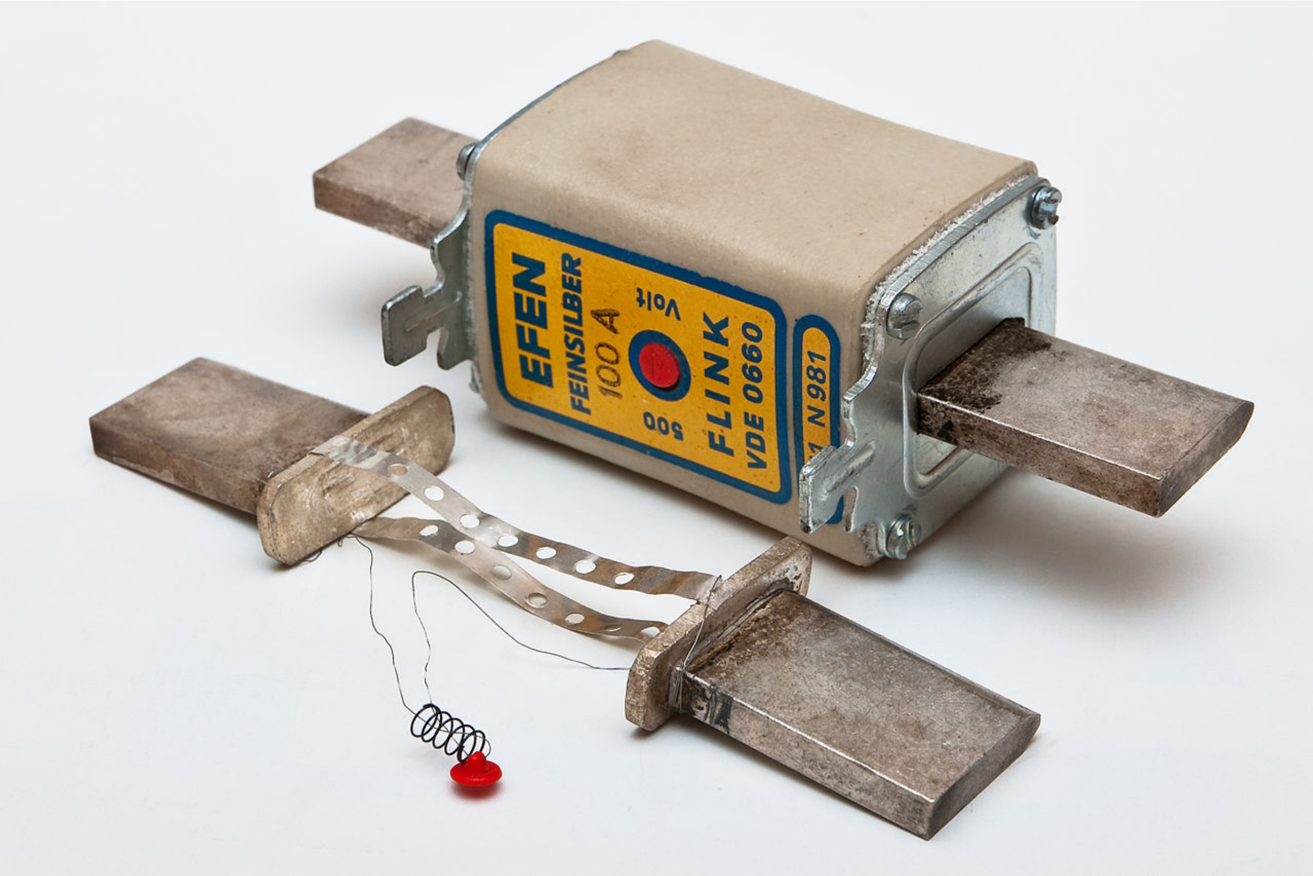
Gold (Au) does not oxidise in contact with air, making it an extremely reliable contact.

Gold is very expensive, so it's mainly used to plate contacts where only the surface properties are important.

The plating thickness is from about 0.25-5 µm.

SILVER

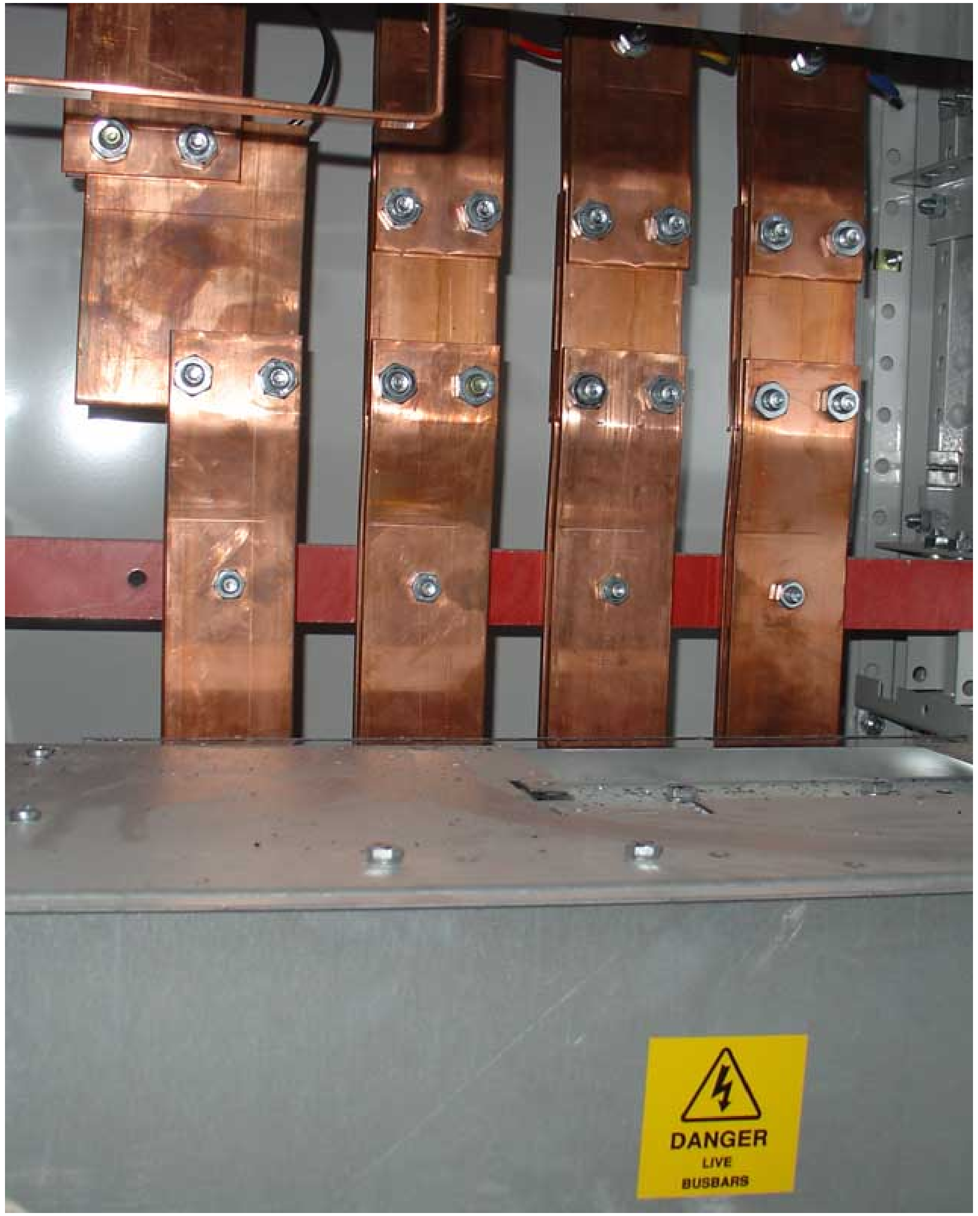
Silver (Ag) is the best conductor – but is very expensive. Silver is very temperature stable even when hot, and is used in high current fuses for this reason.



COPPER

Copper (Cu) offers the best balance of workability, conductivity and price for most small scale wiring.

Copper is less often used in power transmission, because aluminium is cheaper and lighter than copper for the same conductivity.



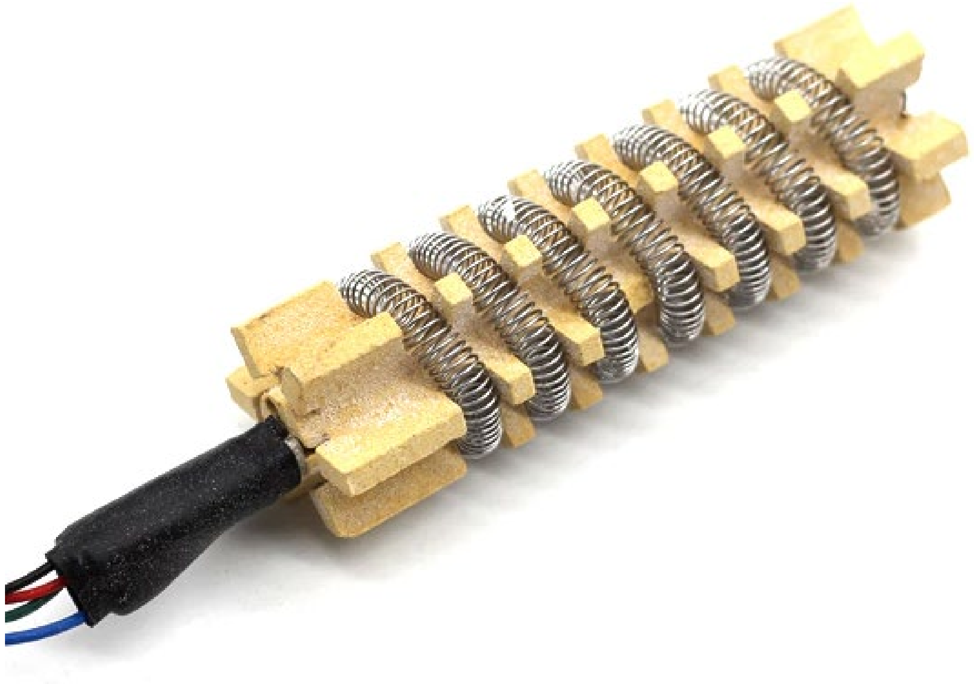
ALUMINIUM

Aluminium (Al) is cheaper and lighter than copper for the same amount of conductivity, but is harder to work in small wire sizes, more bulky and less stable than copper.

The sample on the right is from the HVDC line from Benmore to Haywards. It also has a steel inner reinforcing cable (inner steel strands) to improve tensile strength.

NICHROME

Nichrome is an alloy of nickel (Ni) and chromium (Cr) and is used for heating elements. Nichrome is corrosion-resistant, has a high melting point of about 1400°C, is cheap, strong, ductile, stable, and has high resistivity.



TUNGSTEN

Tungsten (W) is used for light bulb filaments due to its extremely high melting point (3422°C).

It is also used for filaments in fluorescent tubes, coated with metal oxides to increase electron emission at lower temperatures.

BRASS

Brass is an alloy of copper (Cu) and zinc (Zn).

It is used in terminals and connectors, as it is harder and tougher than copper. It has poorer conductivity than copper and is not very flexible.

The plug on the right has brass pins. Sometimes the brass is coated with nickel to improve oxidation resistance.

CARBON

Carbon (C) is not a good conductor, but is self-lubricating. Carbon is used for brush contacts on rotating parts. The high resistance of the brushes across their face also aids with commutation during rotation by making sure that the coils don't get shorted.

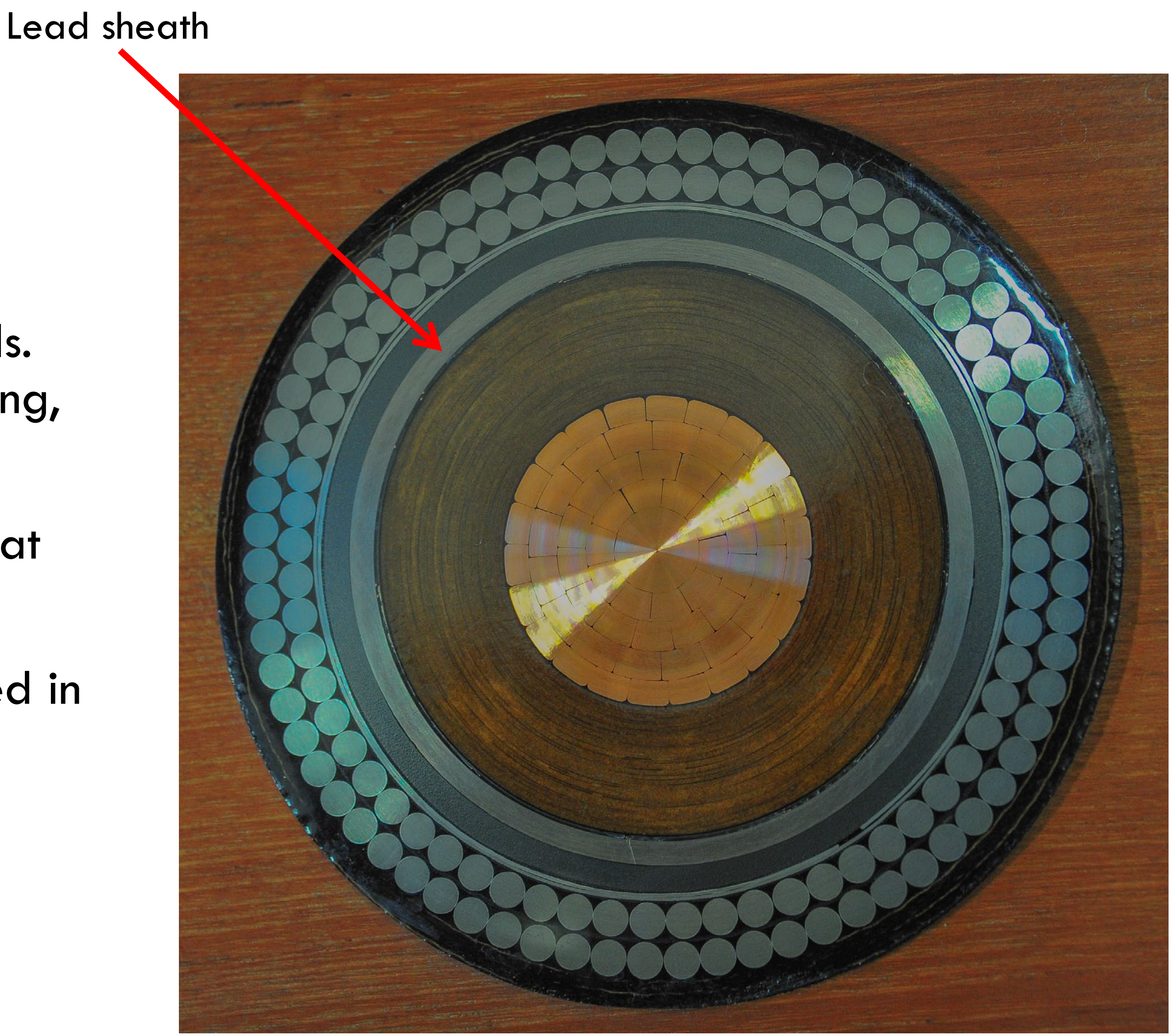
The picture at right shows a set of carbon brushes used on a car starter motor. Normally only a couple of mm of brush would be visible.

LEAD

Lead (Pb) has a much lower melting point (328°C) than most other metals. Lead is often used for cable sheathing, and for joining wires by soldering.

Solder is an alloy of lead and tin that melts at about 180°C.

Lead and lead dioxide are also used in lead-acid batteries as the active materials.

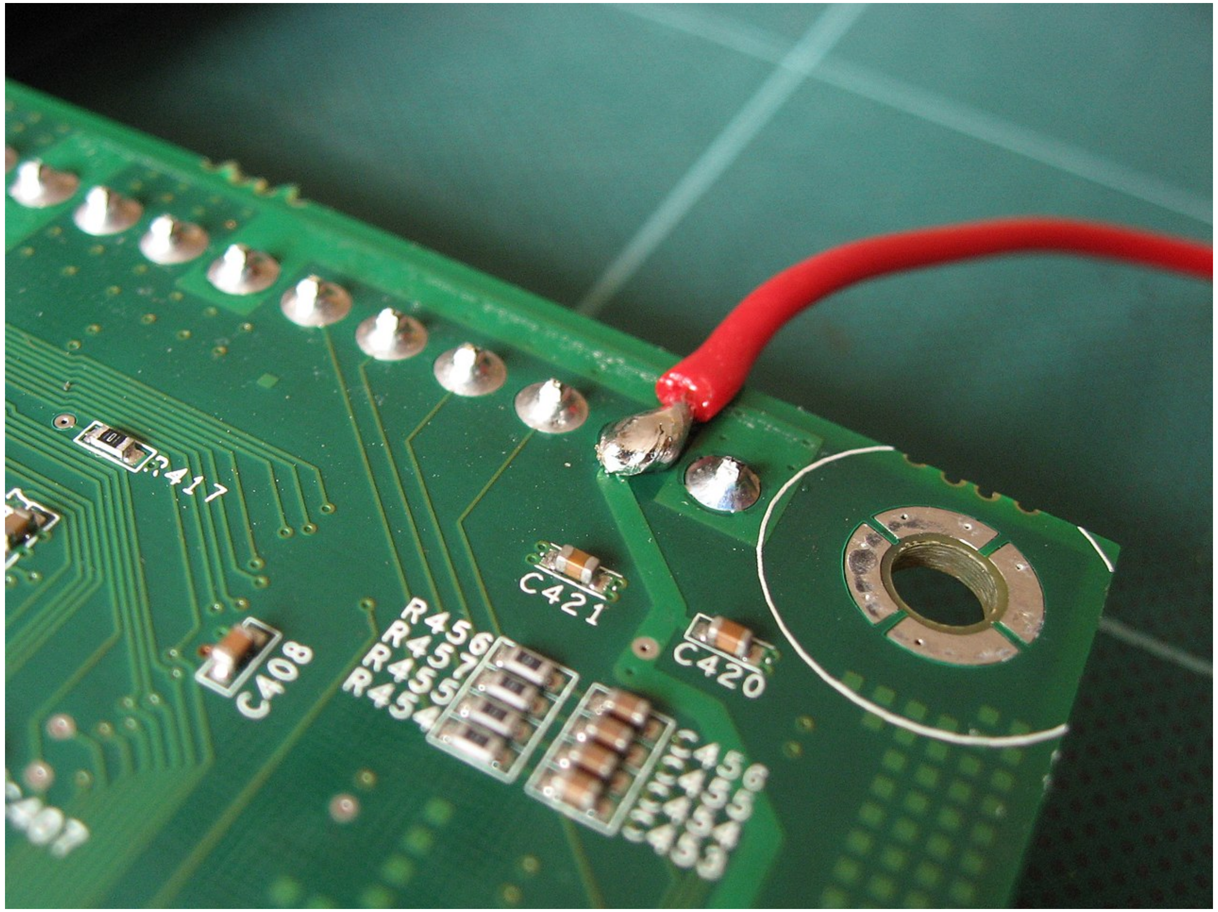


TIN

Tin (Sn) has a much lower melting point (232°C) than most other metals. Solder is an alloy of lead and tin that melts at about 180°C. A global phase-out of lead in electronics means that lead-free solder, which is mostly tin, is in widespread use.

Copper wires in high temperature wiring is tin plated to protect against corrosion.

The picture on the right shows many soldered joints.



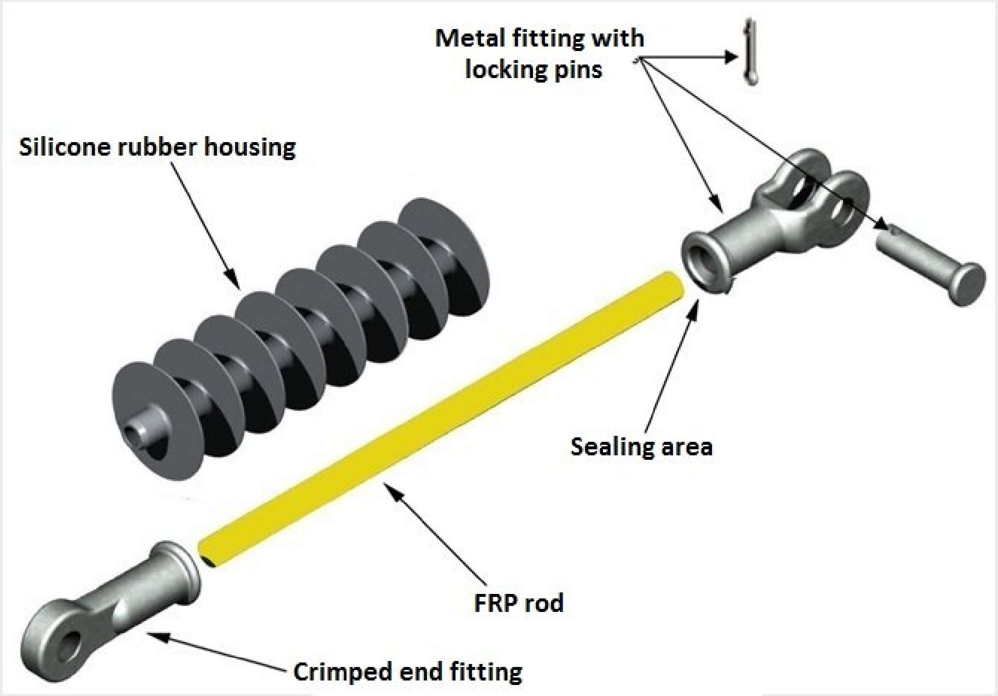
EXAMPLES OF INSULATORS

COMPOSITES

Composites aim to get the "best of both worlds". Many insulators are made of a stiff fibreglass reinforced plastic core for tensile strength, clad with silicone rubber for weather resistance.

They aim to be lighter, tougher and easier to handle than single-material insulators.

The main disadvantage is that they are custom-made for a given voltage.



AIR

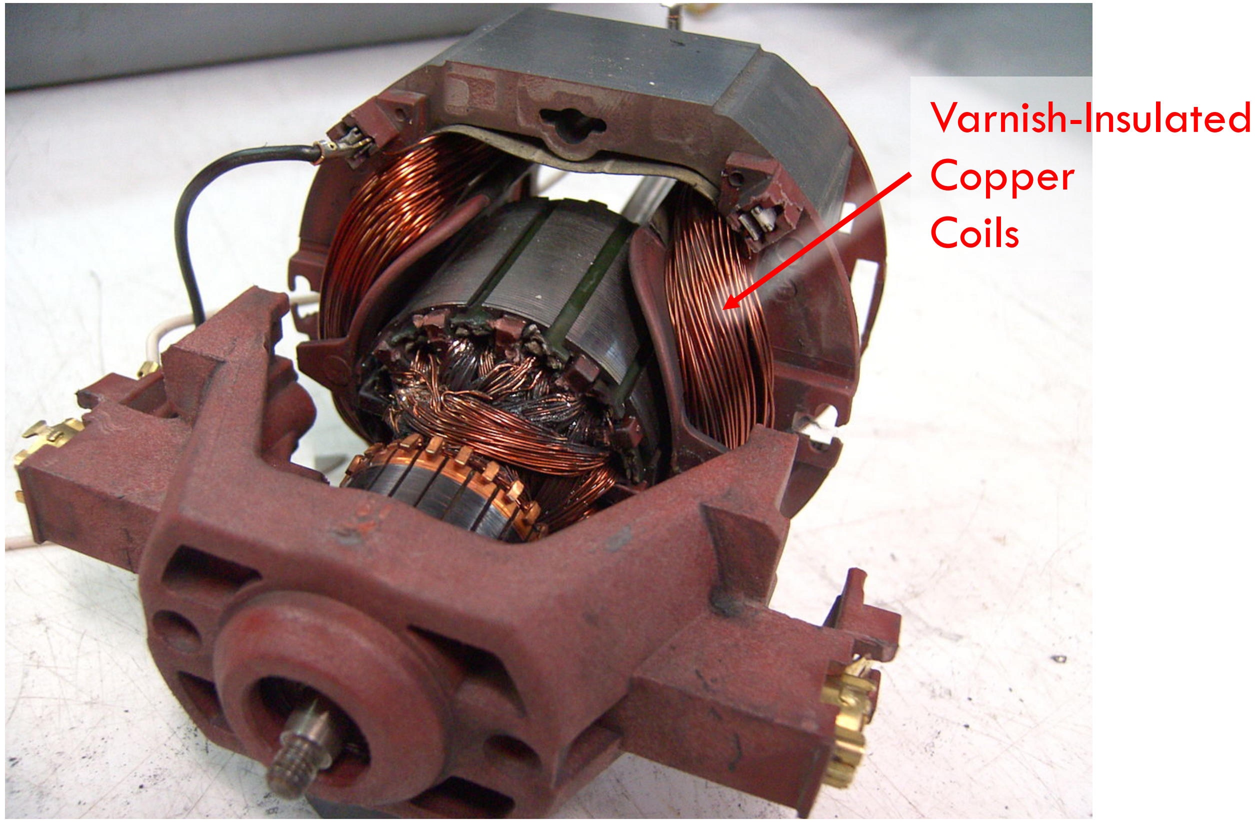
Air is a fluid and is a very good insulator, and being a fluid it is ‘self healing’ if there is a failure. It’s also extremely cheap and self-renewing.

VARNISH

Varnish is used in wound coils such as motors and transformers, where space is at a premium. “Magnet wire” is insulated with a thin layer of varnish.

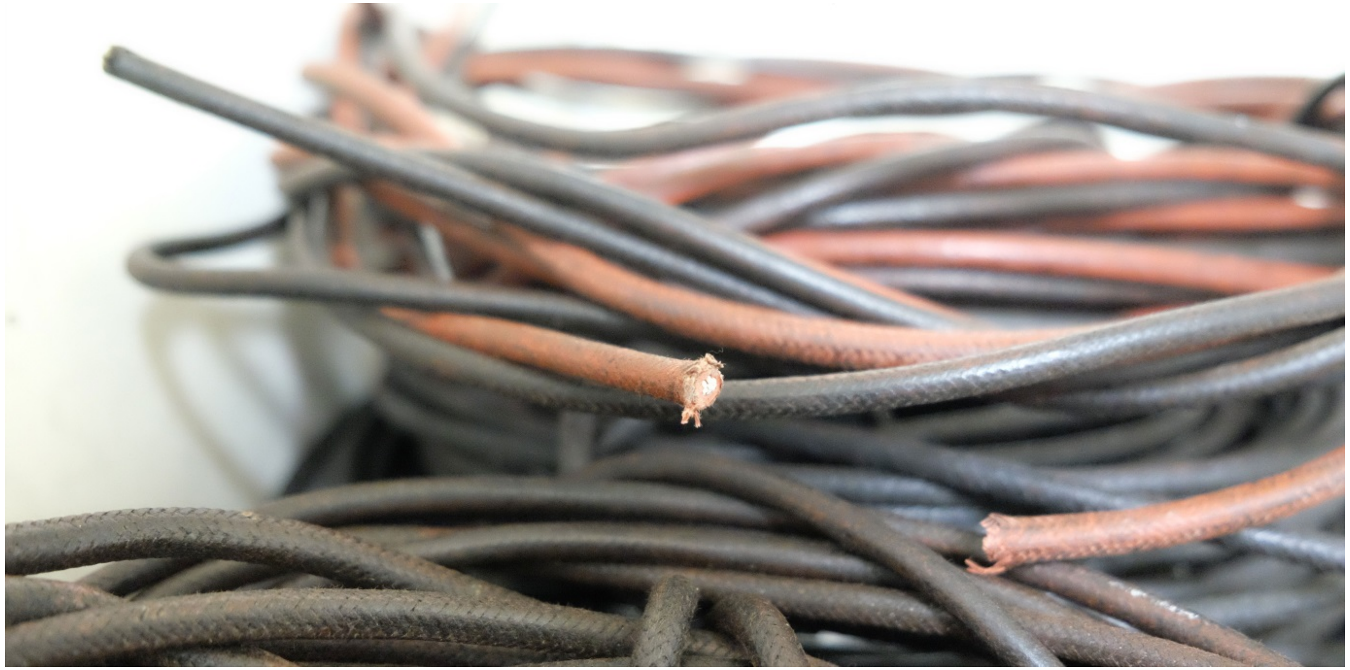
The windings on the universal motor at the right are insulated with varnish.

Varnish can also be used to hold coils together against vibration and rotational forces.



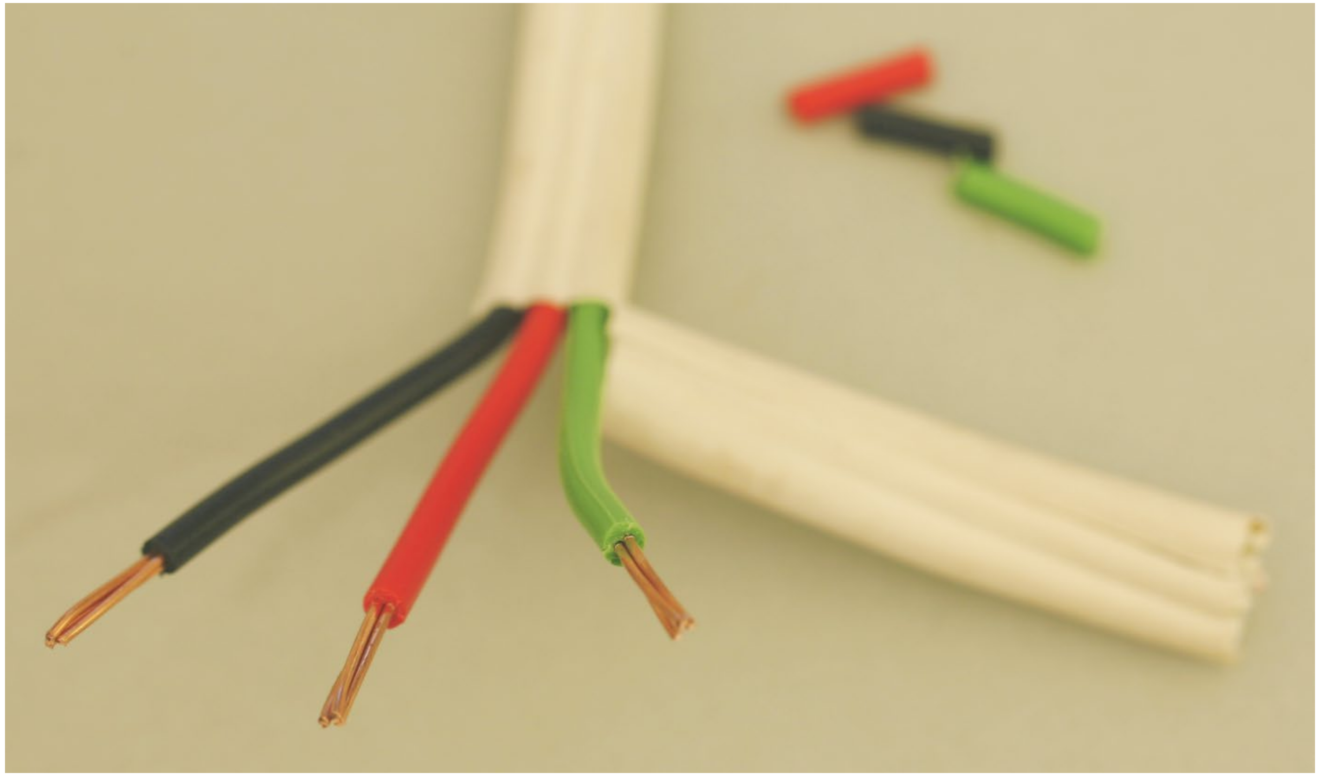
RUBBER

Rubber has been used in the past, but tends to perish with heat and air exposure, making it liable to fall apart and fail. Copper used with rubber insulation must be tin plated to prevent corrosion.



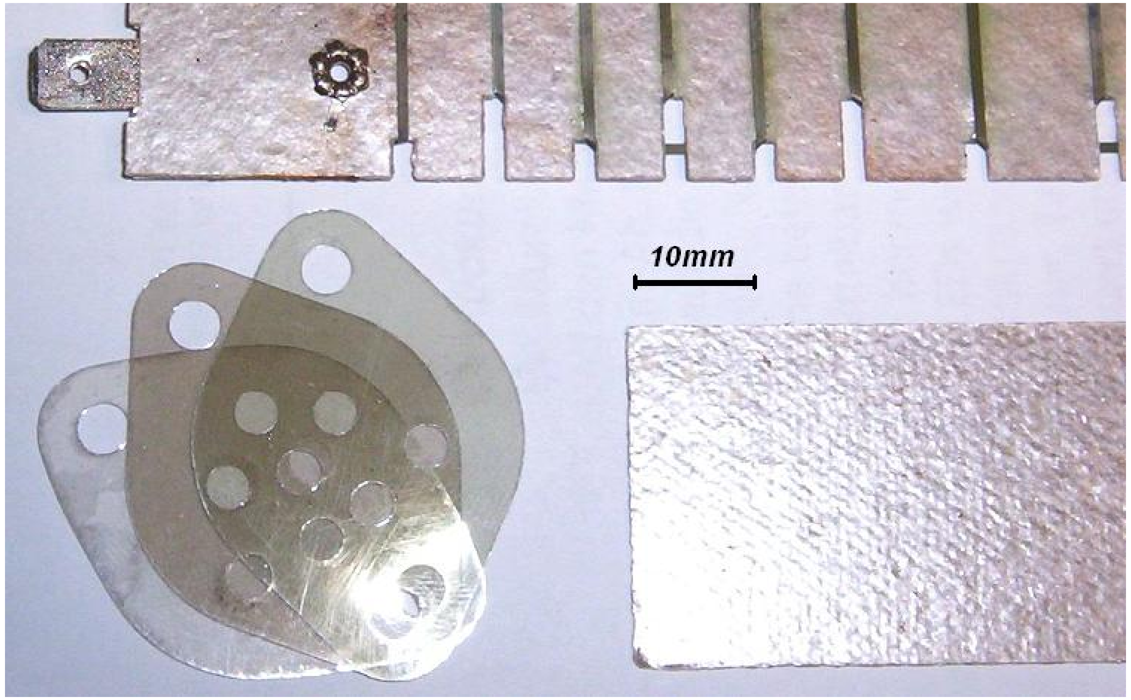
PVC

PVC is low-cost, durable, easy to work with, and easily formed and coloured. PVC is the material of choice for insulation of TPS (tough plastic sheath) building wiring when no other special properties are needed. PVC is not high temperature or solvent resistant, and can release toxic fumes when it burns.



MICA

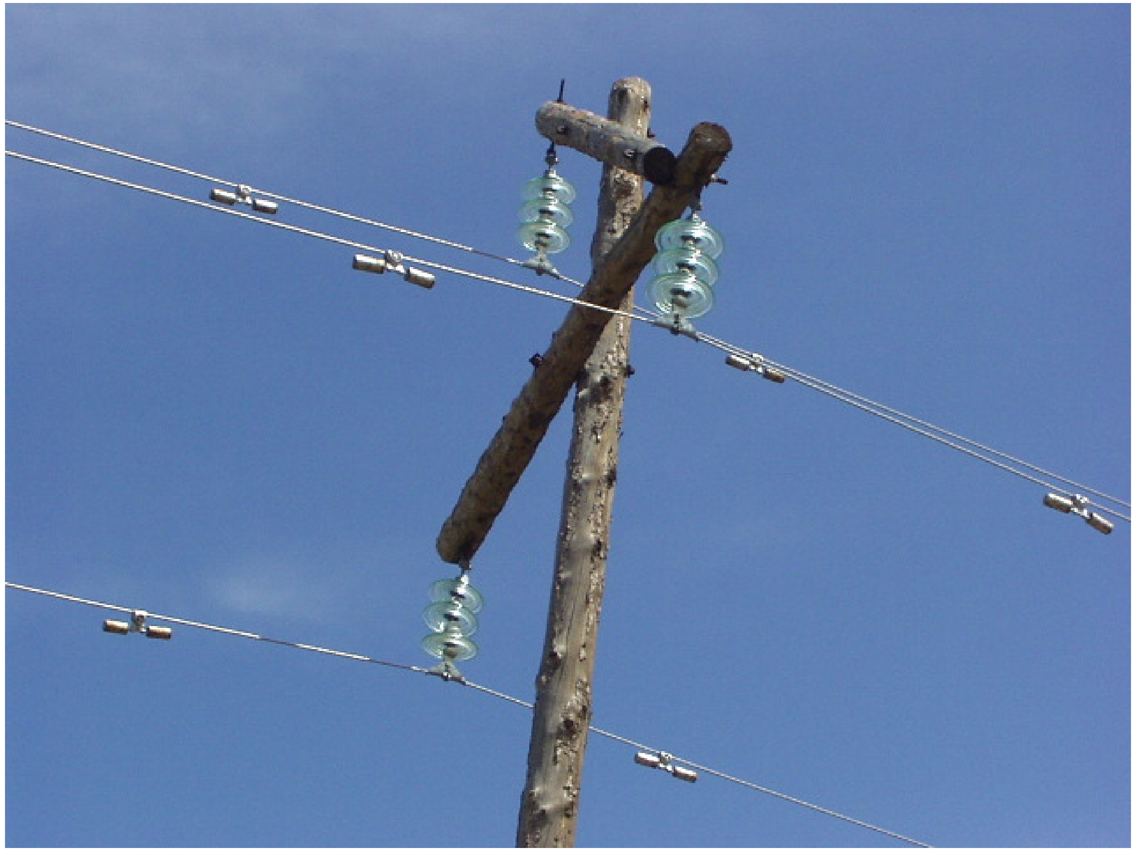
Mica is a mineral able to be formed into sheets, and it has extremely good heat resistance. Toaster elements are formed on a mica base. Mica is not flexible.



GLASS

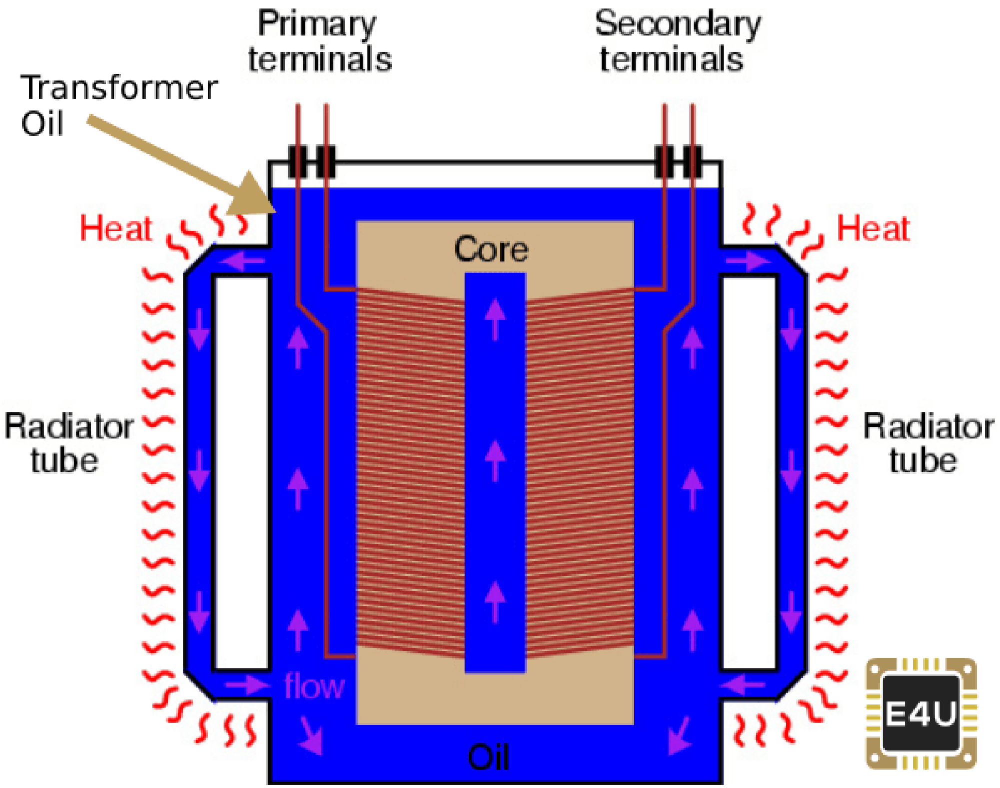
Glass is low-cost, durable, and easily formed and coloured. Glass is frequently used for insulation of transmission lines in outdoor use. However, glass is heavy, brittle, inflexible, and difficult to form in large single sections as it must be worked when hot.

Glass insulators for higher voltage lines are made up of multiple individual insulators.



OIL

Oil is a fluid used for filling the inside of transformers and other high voltage switchgear. Its functions are to insulate, suppress corona discharge and arcing, and to serve as a coolant. Oil can be messy and difficult to handle, and is flammable.



CERAMICS

Ceramics are a family of materials that are fired in a kiln to produce a hard, durable insulator. Very hard and high temperature resistant, but not flexible.

TEMPERATURE COEFFICIENT

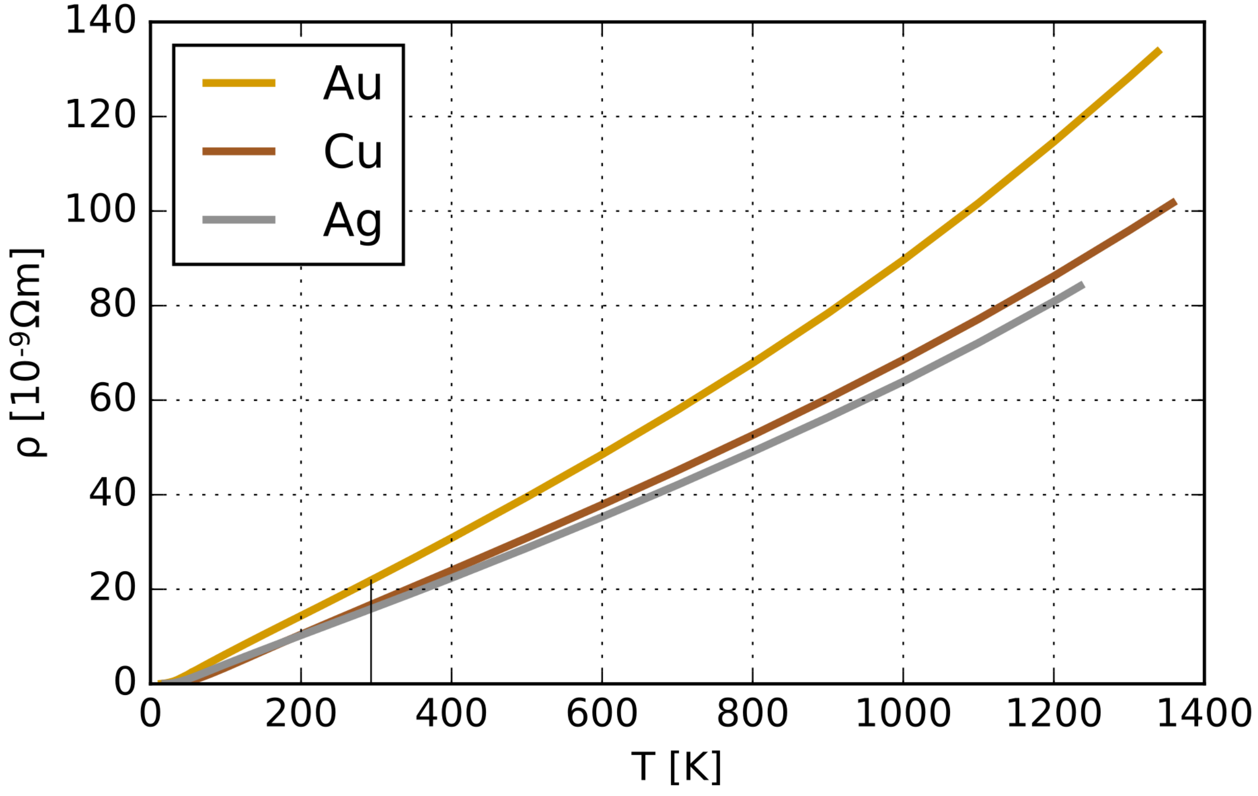
TEMPERATURE COEFFICIENT OF RESISTIVITY (TCR)

The temperature can affect the resistivity of a substance.

Pure metals usually have a *positive* TCR. These are referred to as PTC (positive temperature coefficient).

Poor conductors or semiconductors (e.g. carbon) tend to have little dependence on temperature or a slight NTC characteristic.

The graph on the right shows resistivity vs temperature for copper (Cu), silver (Ag) and gold (Au). Notice the increasing resistivity with temperature.



TEMPERATURE COEFFICIENT OF RESISTIVITY (TCR)

Some materials are specially designed to have a certain temperature coefficient.

NTC materials can be used as temperature detectors.

PTC materials can be used as “self regulating heaters”.

Materials with a stable resistance with temperature are useful for heating elements. Nichrome is an example.

TCR - EXAMPLES

Silver: 0.00380 K^{-1}

Copper: 0.00404 K^{-1}

Gold: 0.00340 K^{-1}

Aluminium: 0.00390 K^{-1}

Tungsten: 0.00540 K^{-1}

Iron: 0.005 K^{-1}

Nichrome: 0.0004 K^{-1}

Carbon: −0.0005 K^{-1}

Germanium: −0.048 K^{-1}

Silicon: −0.075 K^{-1}

Temperature coefficients of resistivity only really apply in this way for conductors and some semiconductors (e.g. silicon, pictured below).

TCR CALCULATIONS

Metals have a TCR that is given as a *linear approximation.*

The TCR is given by α (alpha).

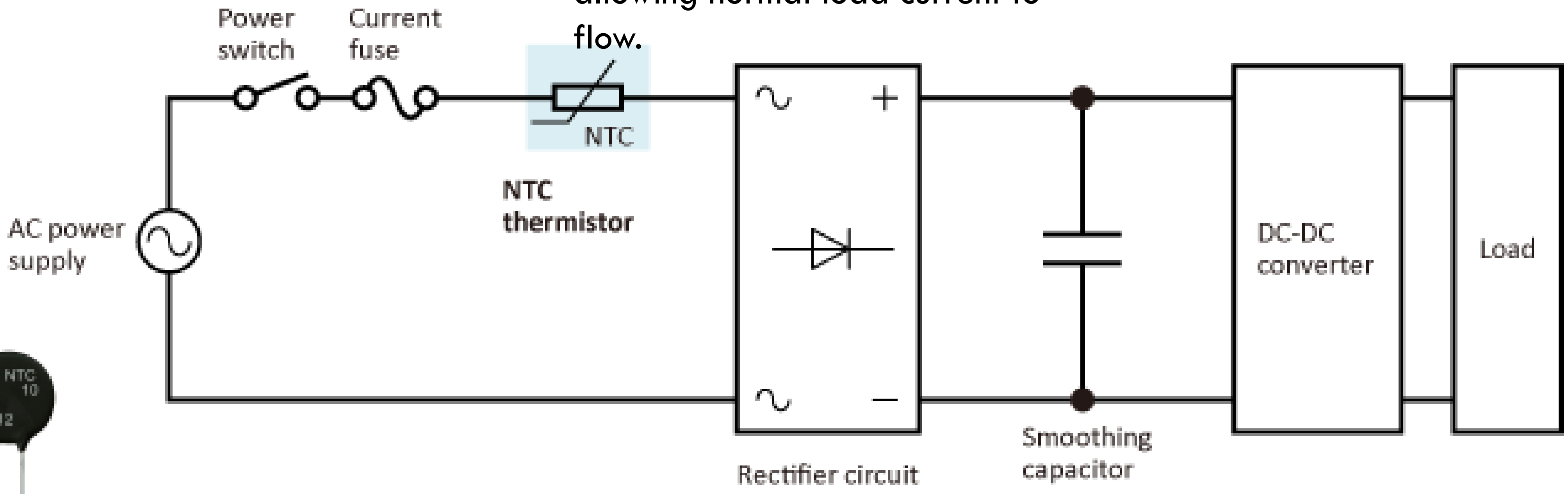
For example, copper has a TCR of 0.00427 K^{-1} (or $°C^{-1}$) at 0°C.

A 1 Ω resistor made of copper will have a resistance of 1.00427 Ω at 1°C, through 1.427 Ω at 100°C.

Beware: α depends on the base temperature.

NTC APPLICATION – IN-RUSH LIMITER

The NTC thermistor has high resistance when cold, then as load current flows the NTC heats up, decreasing its resistance and allowing normal load current to flow.



PTC APPLICATION – SELF-REGULATING HEATER

The PTC thermistor has low resistance when cold. This causes current to flow, and the device to heat.

PTC heaters are designed to “flip” to a high resistance state at a certain temperature.

The lowered current reduces the heat output. A point will be reached where the current flow maintains the temperature.

The temperature can be tailored by changing the PTC material.